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GAMMA RAY OBSERVATORY NICKEL-CADMIUM BATTERY EVALUATION

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ABSTRACT

An assessment is made concerning the status of GRO's battery and cell problems to assist the GRO Program Office with a risk assessment of its flight nickel-cadmium cells. Battery options were developed and submitted to provide the program with assistance in getting the best possible batteries for an April 1990 launch readiness date. Results are presented based upon the status of the data received at the time of the review with the recognition that additional data would be forthcoming possibly changing positions.

ACKNOWLEDGEMENTS

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GAMMA RAY OBSERVATORY NICKEL-CADMIUM BATTERY EVALUATION

1.0 PURPOSE

The NASA Aerospace Flight Battery Systems Steering Committee, during the 10th Committee meeting on February 7, 1989, reviewed the status of GRO's battery and cell (Gates) problems to assist the GRO Program Office with a risk assessment of those nickel-cadmium cells.

The purpose of the evaluation, requested by GRO program management, was to bring forth the best NASA technical experience and expertise on cell and battery systems to determine, by an independent review process, the nature and magnitude of the risks involved and to provide recommendations to the GRO Program Office concerning actions and options.

No conclusions are provided herein relative to launch recommendations. The Committee considers the launch decision as a program function, one based upon all program facets, including inputs such as this one. This report is, therefore, submitted to provide the program with assistance in getting the best possible batteries for an April 1990 launch readiness date.

Provided below are the results of the collective evaluation of the battery and cell technical risks, recommendations, and some suggested options.

2.0 BACKGROUND

2.1. Previous Involvement with GRO.

Cell problems with the Gates nickel-cadmium chemistry cells had been brought to the attention of NASA senior management during the Annual Program Review in March 1988. During that meeting a special review was chartered by Mr. Rodney, Associate Administrator for Safety, Reliability, Maintainability, and Quality Assurance, to independently establish the impact of the suspect Gates Energy Products cells on NASA's flight programs.

Based upon a very substantial, 25-30 year data base, the conclusion for the GRO Program in its report to NASA senior management, May 1988, was that the GRO cells were expected to produce good flight results. The GRO cells contained the attractive design features of the NASA Standard that had been proven to be conducive to long life times in low Earth orbit (LEO). Experience with the NASA Standard cell design shows it functioning satisfactorily in flight whenever the cells' manufacturing and testing processes had received the proper control and attention (Hal). That data base constitutes the primary reference by which to judge the acceptability of nickel-cadmium cells for flight. While the NASA Code Q Battery Program has initiatives under way or planned to be accomplished for remedying the process control situation, including the objective of acquiring a better understanding of the cell's internal functional processes, that activity will require years to complete plus additional time to confirm the results by testing.

Being concerned about the performance of the GRO Lot 16 NASA Standard cell test results and the anomalous data, as well as being concerned about the GRO Lot 17 accident, a risk assessment of GRO's battery situation was conducted in an effort to support the Headquarters GRO Program Manager as well as to better understand the technical nature of the problem. Therefore, during the Steering Committee met on February 7, 1989 initiate this GRO cell risk assessment.

The risk assessment first proceeded with a review of the Goddard data and the options for risk abatement. Discussions then ensued concerning the interpretation of the results and the best cell alternatives for GRO. A more in-depth, extended investigation was considered but deferred to this one in order to be more timely and responsive to GRO's needs. There were in addition, numerous telecons to revisit discussion points and to consider some new options which were unknown at the time of the Committee meeting. Teleconferences were held on February 24 and 27, 1989 to discuss the changes since the JPL meeting. Other telecons with numerous members of the battery community were held to discuss the data and the appropriate actions.

2.2. Issues with Lot 16 and Lot 17 Cells.

Two problems occurred affecting the GRO cells -- a test procedural error with Lot 17 and a test anomaly with Lot 16.

A Gates test operator inadvertently overcharged 17 cells in Lot 17 that were in a full state of charge at the time of the accident.

With cell Lot 16, significant cell voltage divergences were observed during the testing of Pack 6051A, test cycle number 3500, on cell number 4. It was operating at 59 mv below the average level of three other "good" cells (39 mv lower than the 5-cell average voltage). There is no specification value for voltage divergence, but the values above were considered excessive. A specification of $\pm$ 8 mv is used for cell matching purposes to install cells into a battery, indicating the importance of close matching of cell voltage. In addition to the divergence of cell number 4, cell number 1 was down by 42 mv from the average of the three "good" cells. Because of the pack's anomalous performance, it was removed from testing for capacity checks. Eventually the pack was returned to test without cell 4.

A brief explanation to understand the battery charging system is necessary. GRO uses a temperature compensated voltage limit charging method (voltage-limit charge control) in which the cell pack is charged to a set pack voltage established by a specified VT curve for the cell design used in the pack. If one or more cells in the pack exhibit lower voltages during the charge, the remaining good cells will compensate for the lower voltage cells by operating at higher voltages. The higher the voltage divergence, the greater the stress that is placed upon the good cells.

Cell voltage divergences of the magnitude experienced with GRO clearly cause great concern, particularly in power system designs where the VT method is used, such as in GRO. Because of the wide spread use of the VT system with Gates cells, a shadow is cast by the cell 4 problem upon any of the Gates nickel-cadmium cells.

3.0 RESULTS AND RECOMMENDATIONS

3.1. Cell Lot 17.

3.1.1 Results.

After the cells had been fully charged, seventeen of the 74 flight cells in this lot had been accidentally subjected by a Gates test equipment operator to a charge rate of C/2 (25 amps) rather than a C/2 discharge rate. The overcharged cells are considered to be potentially damaged to such an extent by the high charge rate for a period of time sufficiently long (42 minutes) that the quality of these cells is considered to be significantly degraded. No cell data were recorded during this overcharge period.

There was a question by Gates on whether these cells were in a full state of charge when the overcharge incident occurred. Even if correct, some time during the C/2 incident, the cells would have gone into an undefined state of overcharge. For a long duration, highly visible, costly program like GRO, the risk of premature degraded life is too high to accept cells in that condition.

The abused cells are unqualified for flight because of that test exposure history. They are considered to pose a risk for meeting the program's electrical power requirements for the required mission duration. The cell design has not been qualified by test to demonstrate a 5 to 10 year life after being exposed to cell stresses of that magnitude. Further, there is no precedent for the flight use of abused cells. The Program Office has superior options to the acceptance of that risk.

Otherwise, the Lot 17 cells, as shown by Figure 1, have exhibited high quality performance characteristics.

3.1.2. Recommendations.

3.1.2.1. It is recommended that these cells not serve as flight cells. On that point, the agreement of the Committee, when polled, was unanimous. Furthermore, there is no reason to proceed with the planned DPA (Destructive Physical Analysis). There is a lack of confidence in the capability of a DPA to predict the anticipated life of the cells. Although there would be technical interest in the results, this is not an expenditure of program funds that can be justified by the Committee. The DPA will not be conclusive in the prediction of cell life. These 17 cells should receive a quality reject and be marked not for flight use.

All cells that serve as replacements within the same battery, or batteries installed onto a common bus, shall contain cells that have been manufactured from the same cell lot. That procedure has been found to produce the highest probability that the cells will exhibit uniform voltage characteristics during the cells' operational life.

3.1.2.2. When the program considers sources of cells for alternative batteries, the first recommendation is that cells manufactured from different lots should not be mixed within the same battery. Cell voltage characteristics can be expected to vary from lot to lot. The objective is to avoid the loss of battery cycle life capability as a consequence of the voltage divergence and the failure to fully charge the cells. Commonly connected batteries, as with the MPS (Modular Power Subsystem), are normally built from cells from the same lot for the same reason.

The second, less preferred, option is the use of batteries, each of which have been fabricated using common lot cells, but which have lots that vary from battery to battery. It is clear that GRO will necessarily use an odd lot battery since there were 74 Lot 17 cells originally available for flight, minus the 17 damaged cells, leaving 57 flight worthy cells. That number is sufficient for only two good batteries from Lot 17, requiring the addition of a third battery from another currently unspecified lot. Those three batteries will be connected to one bus. Our concern is that one electrically different battery may degrade the performance of the other two batteries. There is no precedence for the use of mixed batteries on an MPS. Because one MPS must have batteries which have been constructed from two different cell lots, it is recommended that the cells for the other MPS all come from the same lot.

The least preferred option is a battery containing cells from mixed lots. Our concern is the deterioration of the entire battery because of cells with diverging voltages. The power system's flight data lacks the numerical granularity and the number of instrumentation sensors that the ground test system contains. Consequently, the use of the remaining 13 good Lot 17 cells mixed in a battery with those from another lot is not recommended. If there is no alternative, then the approach which the program should use is to fabricate a battery from cells exhibiting the closest matched electrical characteristics.

3.1.2.3 From a lessons learned perspective, the program should take the appropriate measures to ensure that the remaining cells are <u>carefully monitored</u> to prevent any further accidents. Every means available to protect the existing good cells as well as the replacement cells discussed in section 3.3 should be used.

3.2. Cell Lot 16.

3.2.1. Results.

In retrospect, a review of the earlier test data now reveals that the two cells in this pack of five experienced voltage divergence very early in the life cycle test at Crane. On initial consideration, it is assumed that the problem can be attributed to a cell manufacturing processing problem. This LEO cycle life test was conducted at 15% DOD and 10 ^{o}C and was nonstressful. Actually, the problem first occurred quite early, at cycle 2100, the equivalent of approximately one third of one year. Refer to Figure 1 for the Lot 16 and 17 packs' cell performance variations with time.

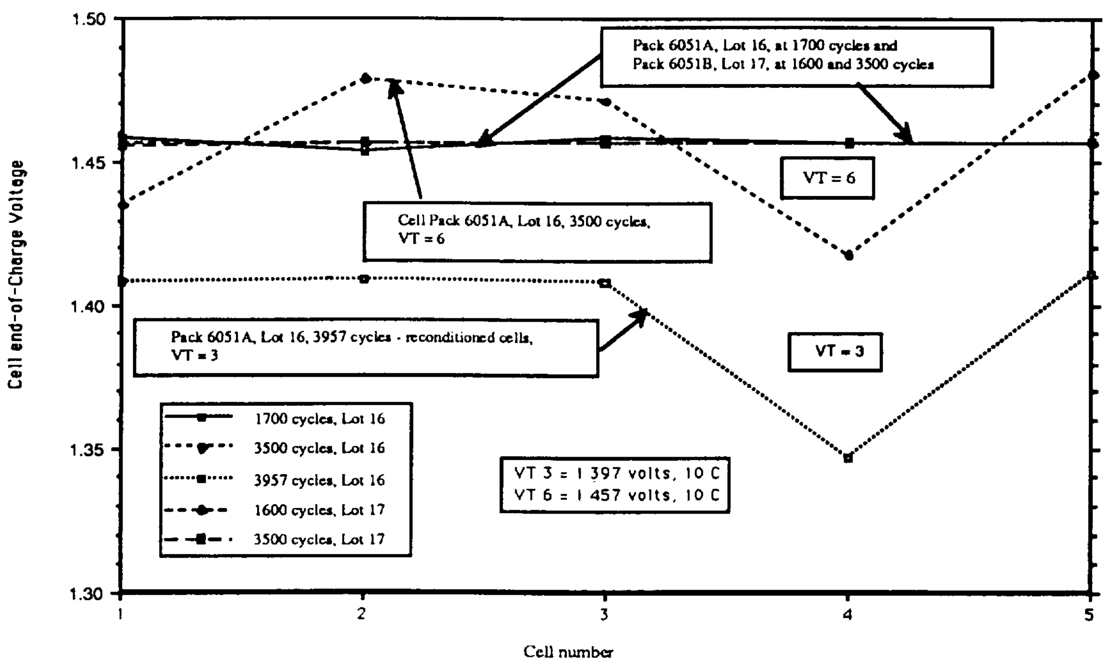

Figure 1. Performance comparison of Packs 6051A (Lot 16) and 6051B (Lot 17) by cell number, as a function of test cycles.

The figure shows discrepant behavior between cells number one and four from the other cells in pack number 6051A. Instrumentation accuracy is ±0.05%. As a figure of merit, a plot of the good Lot 17 pack number 6051B cells is included to illustrate their performance characteristics at 1600 and 3500 cycles, basically a flat curve with a one sigma deviation of 1.6 mv at 3500 cycles. Observe, too, that the performance of the Lot 16 cells at 1700 cycles matches identically with the Lot 17 cells at 1600 and 3500 cycles. That is the performance level expected from properly performing cells.

Notice that the 3 good cells in Lot 16 shifted higher than Lot 17 at 3500 cycles. This is attributed to the VT control system raising the voltage level of the good cells to compensate for the voltage degradation of the malfunctioning cells. This stresses the good cells by operating them at a higher voltage while degrading the low voltage cells. The average pack voltage is maintained at the required level of 1.457 volts. This shows the importance of cell matching.

At 3500 cycles cell number 4 was observed at 1.418 volts at the end of charge while operating at the VT 6 charging level. The cells were removed from test (3512 cycles) and a capacity check made on all five cells. A diverging capacity was the result. Because the cells had been allowed to stand open circuited for 5 weeks, from November 7 to December 14, 1988, when the capacity of each cell was checked, some question was raised over the validity of the results. The data are presented in Table 1:

TABLE 1. PACK 6051A CELL CAPACITY MEASUREMENTS

CELL NUMBER	5 WEEK OPEN CIRCUIT, AH	RECONDITIONING	POST RECONDITIONING CAPACITY, AH	CAPACITY CHANGE, %
1	36.3		64.9	44
2	58.1		64.9	10
3	51.2		64.9	21
4	14.1		64.9	78
5	58.5		64.2	9

The cells' five week open capacity performance, shown in Table 1, is indicative of the results that one would expect considering the divergence. Cell 1, which exhibits anomalous capacity performance that is less severe than cell 4, has a higher charge capacity than cell 4 but still below the remaining good cells. As a result of the cells being in a state of open circuit during that period, a condition which is not to be encountered in orbit, there was some question as to the effect on the capacity measurements that the 5 week open circuit stand period may have had. The 5 cells were, therefore, fully reconditioned to 0 volts and recharged with the result that the 5 cells were found to have a capacity of approximately 65 AH. That capacity recovery is considered to be typical of reconditioned cells, even those degraded. The pack was returned to test (January 7, 1989). A VT = 3 voltage control level (1.397 volts) was initiated at 3880 cycles (January 26, 1989) to attempt to recover the degraded cell 4 performance. The intent here was to control the divergence by lowering the VT limits, and then to gradually increase the VT limit to the desired level, once the divergence was controlled. Cell 4 diverged again, this time to 1.347 volts. Cell number 1 returned to a performance level consistent with cells 2, 3, and 5. The cycle life history of cells 1, 4, and the average voltage of cells 2, 3, & 5 are compared in Figure 2 to graphically compare the anomalous cell characteristics.

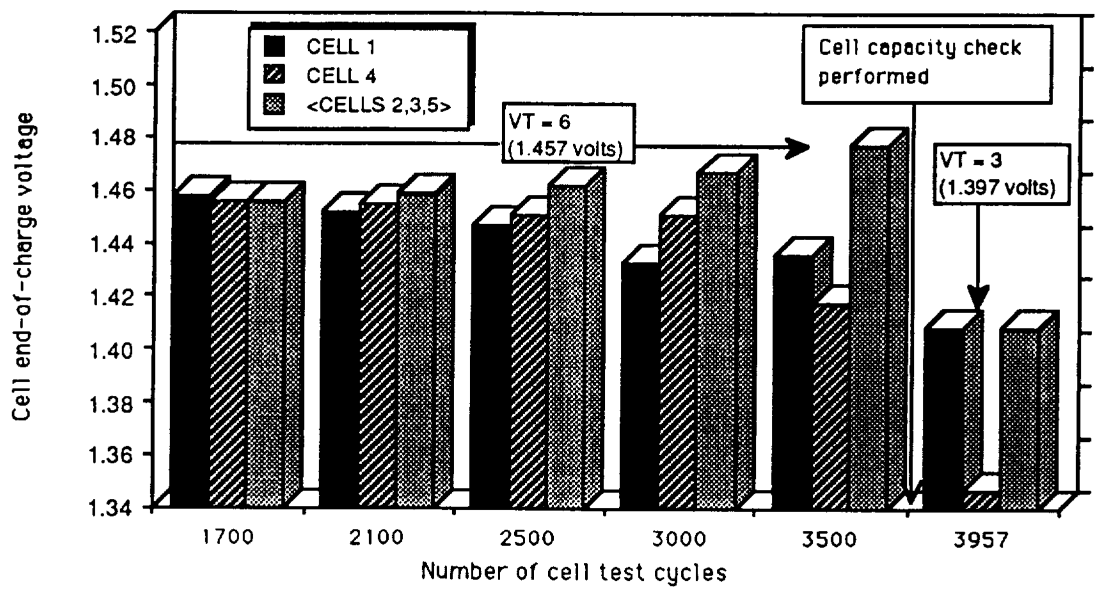

Figure 2. GRO, Lot 16, cell numbers 1 and 4 voltage degradation as a function of life cycles.

- At 1700 cycles, Figure 2 shows consistent performance among the 5 cells.

- As cell 1's voltage decreases at 2100 cycles, the charging circuit increases the voltage of cells 2, 3, and 5 to maintain the average pack voltage for VT = 6. Cell 4 diverges from operating at the higher voltage level of cells 2, 3, and 5.

- At 2500 cycles, the cell 4 voltage decreases below its 1700 cycle value, and cell 1 descends further. Meanwhile, the mean Σ 2, 3, 5 cell voltage rises higher to compensate for the divergence.

- At 3000 cycles, a further decrease occurs in cell 1's voltage and cell 4's voltage remains unchanged. Cells 2, 3, and 5 rise higher.

- At 3500 cycles, cell 4's voltage rapidly descends, and cell 1 commences to ascend, perhaps in response to the low voltage of cell 4. The mean Σ 2, 3, 5 cell voltages increases further to maintain the VT = 6 pack voltage control level. The individual values for cells 2, 3, 5 were not plotted since they were matched closely within a one sigma value of 3.7 mv.

- At 3512 cycles, the Pack 6051A was removed from testing, its cells' capacities checked, cells reconditioned, and returned to test.

- At 3989 cycles, cell 4 degraded further, and the was cell removed on February 2, 1989 from further testing in the pack. Notice that at the VT = 3 level, cell 1 is now being controlled to operate at a lower voltage level than the voltage to which it had previously degraded. Pack 6051 A was returned to test after cell removal and cycled for 62 cycles at VT = 3, then incrementally increased to VT = 4 (+68 cycles), 5 (+62 cycles), 6 (+61 cycles, February 21, 1989). Cell 1 has maintained a voltage level consistent with cells 2, 3, 5, the difference between those 4 cells being 2 mv.

The cells' performance characteristics in Pack 6051A, however, have now been altered by the procedure which called for the cell capacity to be checked following cycle number 3512. Whenever cells are taken off test for a capacity check, the cells are deep discharged. That is a procedure which, in effect, reconditions the cell; but it is a procedure which cannot be accomplished in flight. Hence, the performance and electrical characteristics of any cell subjected to a capacity check during a pack test can differ from flight cells where the reconditioning circuitry is not available.

Two points are important concerning the above sequence as an indicator of Lot 16's performance. First, no means exists to establish the effect of the three reconditionings of cell 1 after cycle 3512. It is important to point out that the test pack's electrochemical characteristics have been altered (improved) and that no similar cell reconditioning capability exists in orbit. The results of the pack testing from here on can be misleading, in an optimistic perspective, since reconditioning tends to temporarily improve cell performance. Second, a good quality, commercial grade nickel-cadmium cell will exhibit a 7% capacity loss per month at the 10 ^{o}C temperature in this test (Lin). Cells 2 and 5 lost 10 and 9% respectively in 5 weeks, indicating nominal performance. Cell 3 was higher at 21%.

There was a question whether the electrochemical condition of cell number 4 was exacerbated by the divergence being allowed to continue in test in the October-November time frame without receiving more prompt attention to VT adjustments. Some of the members were of the opinion that some degree of cell voltage recovery may have been achieved or reduced voltage divergence had been possible with an earlier readjustment of the VT level.

There is at least one defective cell in Lot 16 with which to be concerned. The failure of cell 4 leads to the question of whether the failure rate is 1 or 2 anomalous cells in 5, or is it 1 or 2 in a lot sample of 75 cells? With GRO's very limited small test sample, establishment of GRO's mission risk on a statistical basis cannot be accomplished, but the available information does provide an indication where the program should be headed to best proceed with an April 1990 launch.

The small, 5-cell test hardware sample is not of great value in illuminating that failure rate -- more test data are needed to gather better statistics. The GRO is expected to have the capability to accept one cell failure without jeopardizing the mission; that is, the system was designed to tolerate one battery failure per MPS. Hence, the failure rate of 1.3% (one in 75) is an acceptable number. But if it is as high as 20% (or 40%, if cell 1 is also considered anomalous, i.e., either one or two in a 5-cell pack), clearly the GRO will not even meet its two year mission, let alone the desire to continue for 5 or more years. The risk which GRO undertakes, therefore, is a function of that error (or failure) rate. Consequently, attention was focused on the means to improve understanding of the failure rate. Those results will, therefore, comprise one key part of the basis for the recommendations provided below, the other part being to establish the cause of the divergence. Although cell 4 had a damaged fill tube, this does not appear related to the problem, particularly since other cells, including some in Lot 17, received greater damage. A helium leak check will be performed on cell 4 during DPA to determine if any leakage path exists.

To summarize the Lot 16 situation, the divergence is assumed to be a manufacturing process control problem, but the proof awaits the DPA. A follow-up report is planned after receipt of that data. The cell design is the proper one for long life, if the cell manufacturing process has been properly controlled. The deliberations and recommendations were structured around the principle that every thing possible should be done to validate the quality of these cells and to determine if they have a reasonable chance of meeting the mission flight objectives. This is the design in which confidence is the highest and the one with cells that are the most likely to be compatible with GRO's 1990 launch date, plus the fact that these cells have 10 months of test time.

3.2.2. <u>Recommendations</u>.

3.2.2.1. The use of Lot 16 cells is the preferred approach pending the results of cell analysis. That lot has the preferred cell design features, and it accommodates the relatively short time between now and GRO's scheduled launch in April 1990. Flight worthiness judgments for these cells are deferred until these special efforts and the DPA have been completed which are expected to produce an understanding of the extent of the problem. All of the other options have less of the preferred design features and very little time left before launch for testing or even manufacturing. Consequently, every effort should be made to determine whether the cells were inadvertently damaged by either improper handling or faulty test procedures. To accomplish that determination, the program, before the cell 4 DPA, should:

a. check for cell shorts,
b. perform an open circuit stand test and voltage recovery test,
c. electrically characterize the cell first, the objective being to determine if the voltage recovers,
d. review carefully the acceptance test data and the Crane life cycle test data in the light of this problem to determine if some aberration, such as the effect of damage to the cells during shipping, may have been overlooked and which could elucidate the problem, and
e. coordinate the above steps and the DPA procedure with MSFC, JPL, and the Aerospace Corporation prior to the DPA.

3.2.2.2. The program should rely upon the real time life cycle testing of Pack 6051A to detect whether a generic problem is indicated by the unexplained loss of cell capacity (Table 1). Consideration was given to suggesting some effort to investigate the unexplained loss of capacity of cells following the 5 week open circuit period. Discussions with several NASA and non-NASA battery and cell specialists indicated that the drop in capacity is indicative of a significant problem. One approach considered for better understanding the severity was to remove charged cells from pack 6051A, allow them to stand for a period of days in an open circuit status after which a check of their capacity could be made. There was also thought given to checking the flight cells after allowing a stand time. The concern was that damage might result to the flight cell's crystalline structure, and the recommendation is not forwarded. However, before cell 4 is taken apart for DPA, it should be open circuit stand tested. A voltage recovery test is recommended if the capacity check repeats the results of rapid loss in capacity.

3.2.2.3. Because the outcome of the Lot 16 testing is uncertain and in order to preserve schedule time for the program, a set of replacement cells (section 3.3) should be pursued as a back-up in the event that the entire Lot 16 is affected. It is assumed that GRO would not be committed to launch if the cell's life projection is 0.5 to 1.0 years of cycle life (3500-6000 cycles).

If the cell divergence had been experienced in flight, it might have been detected earlier and VT adjustments made more quickly, possibly extending the life. Unfortunately, the flight measurement capability in GRO is not as accurate nor as extensive as the ground system. Instead, in the absence of individual cell voltages, the spacecraft's instrumentation system uses current measurements only on a per battery basis which lacks the ground system's granularity and capacity for examining the performance of individual cells. There is also a capability to measure the half battery voltage, which could be of value in signaling the divergence of unequal cells.

If the Lot 16 problem is generic, then the defect is wide spread across Lot 16, and the GRO mission success could be impacted in terms of lifetime. Determination of the degree to which other cells may have been impacted is important to better define the program's battery risks. That is the basis for the following recommendations which have the objective of expanding a small cell data base as well as conducting stress testing in order to cram as much test time as possible into the short time remaining before launch.

3.2.2.4. Regarding testing, the recommendations made comprise the following actions:

a. Additional confidence building stress tests should be initiated on the remaining spare Lot 16 cells as soon as possible to better define the statistical degree of the defect.

b. Also, tests should be initiated on the proposed replacement cells, section 3.3, as soon as possible.

These tests will serve the two essential functions of providing flight judgments on the acceptability of Lot 16 cells for flight and to preserve valuable time before launch to obtain and to test the replacement cells -- only one year away.

To accomplish the confidence building tests for Lot 16, two test packs were preferred: a stress test and real time life cycle test. The limited number of spare cells in Lot 16 is sufficient for only one pack.

Even if the DPA following the special steps in recommendation 3.2.2.1 above satisfactorily explains the anomaly as a manufacturing processing error, it would still be considered important to commence testing of 5 spare Lot 16 cells now in order to obtain an expanded statistical data base and thereby establish the cell quality of Lot 16. The NASA stress test -- 40% DOD, 20 ^{o}C -- should be conducted in lieu of the real-time test since it provides data on a more rapid turnaround and is needed to better define the statistical nature of the defect. The NASA Standard cell design (comprising unpassivated plates and 2505 separator) when manufactured properly, typically yields 2 years of LEO cycle life under the stress test. A two year successful stress test is considered the equivalent to five years of real-time testing. It should be emphasized that these life extrapolations are guides, not absolute numbers.

3.2.2.5. From a lessons learned perspective, the program should ensure that the remaining cells are carefully monitored to accomplish timely changes in

VT levels in the event that voltage divergences are experienced again. We should use every means available to protect the existing good cells as well as the replacement cells discussed in section 3.3.

3.3. Recommendations and Options for Alternative Cells.

3.3.1. Schedule Protection Option

A schedule protection option is advisable. Use of alternative new cells would help to preserve the schedule: UARS flight cells, TOPEX integration and test cells, and the Explorer Platform (EP) flight cells.

As a consequence of the Lots 16 and 17 problems, the number of "good" batteries for GRO has now decreased from six to two known "good." The possibility exists that the Lot 16 cells do not yield the desired performance and would, in that case, require replacement. If the TOPEX cells are used, the GRO cells can serve as replacement cells for integration and test purposes where the consequences of cell cycle life failure are benign. If the UARS and Explorer Platform flight cells are the ones of choice, clearly a set of alternative cells should be ordered for those programs.

3.3.2. Cell Design Options for GRO

The alternative cell design options for GRO, listed in descending order of preference, are:

(1) Unpassivated plates and 2505 separator -- qualified in 1975. That is the NASA Standard and the preferred design, having a 25 year data base.

(2) Unpassivated plates and 2536 separator -- unqualified. This design has unknown life performance capability. This design failed the separator requalification testing in 1987 as efforts were under way to recertify a new separator material.

(3) Passivated plates and 2505 separator -- unqualified and plate process out of control. This cell design uses a plate manufacturing process that NASA has not endorsed as a replacement for the Standard cell design. From the standpoint of NASA testing, it is an unknown with an unknown life performance capability since the configuration is untested by NASA. Used by industry, mainly in GEO, and has some limited Air Force use in both LEO and GEO.

(4) Passivated plates and 2536 separator -- failed qual. As with (3) above, this is not a NASA approved design. It has been tested and known to yield a short LEO life. Its use is restricted to short (~1 year), nonstressful missions and is therefore not a recommended GRO option. Some test data was recently reported by industry to be good for very small capacity cells (10 AH).